



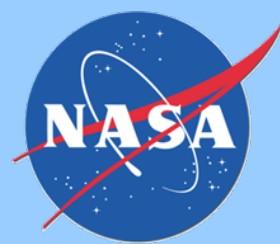
Intelligent Integrated System Health Management

Fernando Figueroa

NASA Stennis Space Center, MS

Presentation at Louisiana Tech

February 3, 2012



Support the rocket engine test mission with sustainable facilities that produce unquestionable measurements, affordably.

A-1



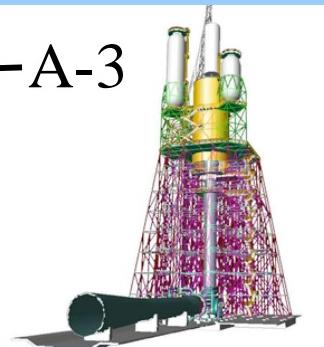
B-1/B-2



A-2



A-3



Others:
•High-pressure Gas
•Industrial Water

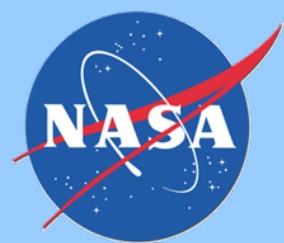
E-2



E-3

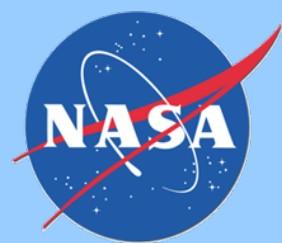


E-1



Outline

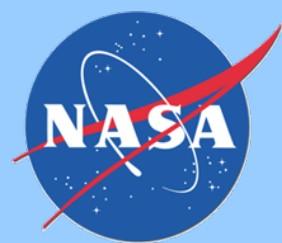
- ISHM Definition.
- ISHM Capability Development.
 - ISHM Knowledge Model.
 - Standards for ISHM Implementation.
 - ISHM Domain Models (ISHM-DM's).
 - Intelligent Sensors and Components.
- ISHM in Systems Design, Engineering, and Integration.
- Intelligent Control for ISHM-Enabled Systems.



Requirements Driving ISHM

Through comprehensive and continuous vigilance

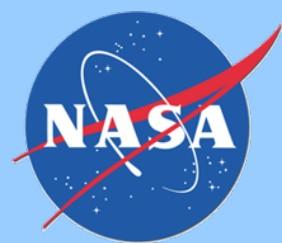
- Improve quality
 - By more accurately understanding the state of a system.
- Minimize costs
 - Of configuration
 - Of repair and calibration
 - Of operations
- Avoid downtime
 - By predicting impending failures
 - By timely intervention
 - By faster diagnosis and recovery
- Increase safety (protect people and assets)



ISHM Objectives

- Use available data, information, and knowledge to
 - Identify system state
 - Detect anomalies
 - Determine anomaly causes
 - Predict system impacts
 - Predict future anomalies
 - Recommend timely mitigation steps
 - Evolve to incorporate new knowledge

ISHM implementation is a problem of “management” of data, information, and knowledge (DIAK) focused on achieving the objectives of ISHM



John C. Stennis Space Center

ISHM Partnerships for Rocket Propulsion testing

A community of Expertise and Technologies

Rocket Engine Test Stand



KSC

Open Systems Architectures



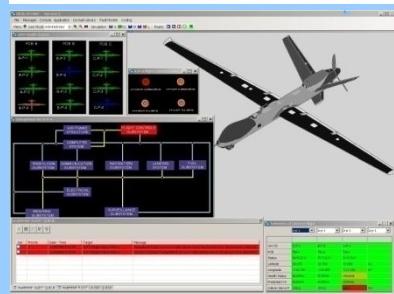
Prognostics & Anomaly Detection



A United Technologies Company



ARC



Proximal Cause Analysis



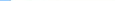
Smart & Intelligent Sensors



Brings you mobility®



KSC



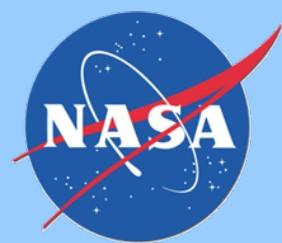
Integrated Awareness

ISS Testbed



JSC

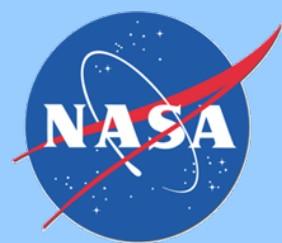




Concepts for iISHM

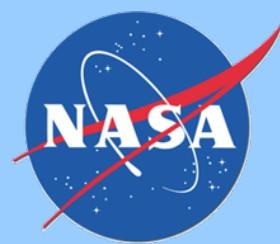
THE CAPABILITY MUST BE CREDIBLE AND AFFORDABLE

- Intelligent System: Manages data, information, and knowledge (DIAK) to achieve its mission (Manage: storage, distribution, sharing, maintenance, processing, reasoning, and presentation)
- iISHM:
 - Employs knowledge about the system embodying “systems thinking” (captures interactions among elements of the system).
 - Is continuously vigilant.
 - Is comprehensive in assessing health of each element of a system.
 - Is systematically evolutionary to achieve higher and higher functional capability levels (increasing effectiveness).
- In order to make this capability possible, the health management system needs to incorporate “intelligence.”



ISHM Definition

- Its own discipline, or sub-discipline under Aerospace Systems Design, Engineering, and Integration.
- Management of data, information, and knowledge (DIAK) with the purposeful objective of determining the health of a system (Management: storage, distribution, sharing, maintenance, processing, reasoning, and presentation).
- ISHM is akin to having a broad-base team of experts who are all individually and collectively observing and analyzing a complex system, and communicating effectively with each other in order to arrive at an accurate and reliable assessment of its health.

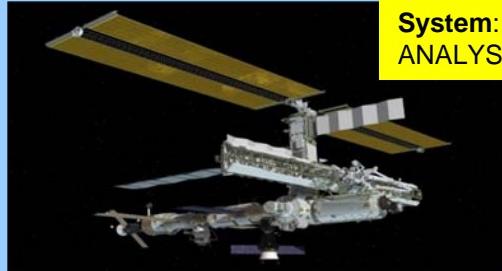


MOVE CAPABILITY TOWARD LEVELS 2 AND 1
DECREASE NEED FOR SUPPORT FROM LOWER LAYERS

People-Based ISHM is Being Done Today

Layer 1
Vehicle/
Test Stand

International Space Station



System: ON BOARD AUTOMATED ANALYS CAPABILITY

Rocket Engine Test Stand



Layer 2
Astronaut/
Test
Conductor



Operator: FASTER, MORE ACCURATE ANALYSIS



Layer 3
Control
Room



Support: FASTER, MORE ACCURATE ANALYSIS
Decreased Need



Layer 4
Back
Control
Room



Support: FASTER, MORE ACCURATE ANALYSIS
Decreased Need

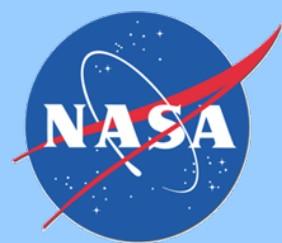


Signal threshold violation detection

Added DIaK from on-board users.

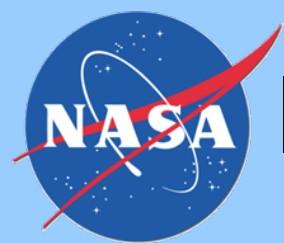
Added DIaK from broad group of experts.

Added DIaK resources from larger community



Determination of Health

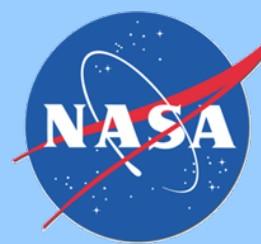
- Use available SYSTEM-WIDE data, information, and knowledge (DIAK) to
 - Identify system state.
 - Detect anomaly indicators.
 - Determine and confirm anomalies.
 - Diagnose causes and determine effects.
 - Predict future anomalies.
 - Recommend timely mitigation steps.
 - Evolve to incorporate new knowledge.
 - Enable integrated system awareness by the user (make available relevant information when needed and allow to dig deeper for details).
 - Manage health information (e.g. anomalies, redlines).
 - Capture and manage usage information (e.g. thermal cycles).
 - Capture and manage design life and maintenance schedule.
 - Enable automated configuration.
 - Implement automated and comprehensive data analysis.
 - Provide verification of consistency among system states and procedures.



ISHM Capability Development

ISHM Knowledge Model

- A plethora of Data, Information, and Knowledge (DlaK) must be applied to achieve high functional capability level (FCL) health management.
- The ISHM Domain Model (ISHM-DM) encompasses DlaK and the tools to implement ISHM capability.



Data, Information, and Knowledge Management Architecture for ISHM (Information Architecture)

**Intelligent
Subsystem
Processes**

**Intelligent
Element
Processes**

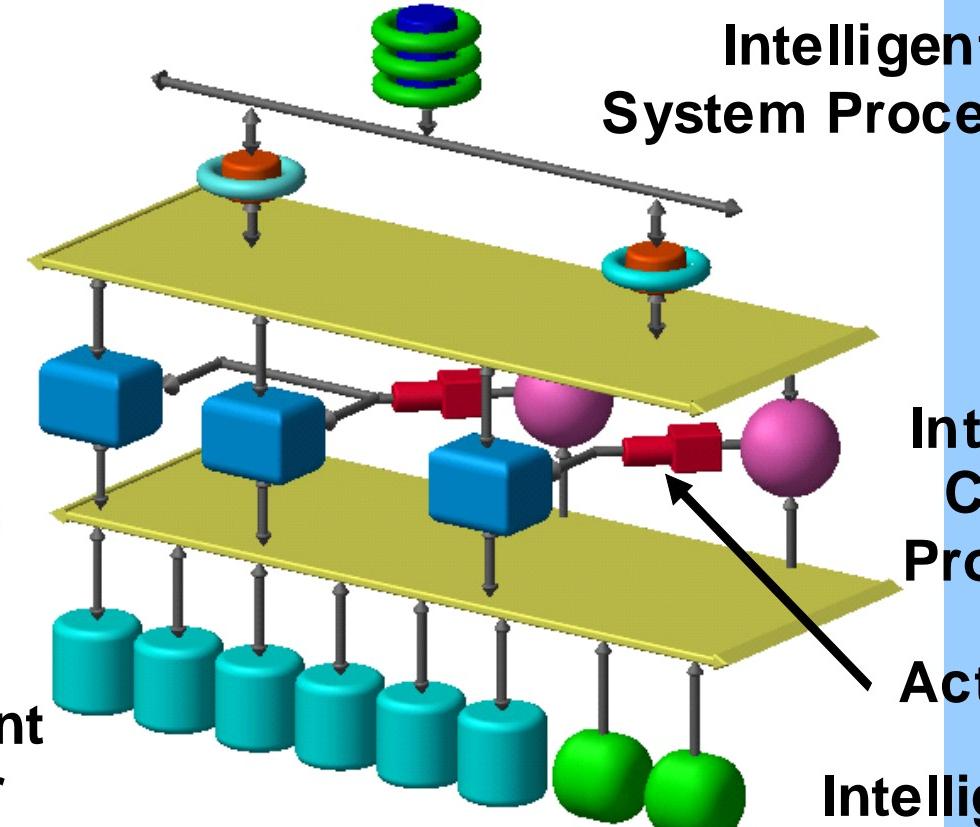
**Intelligent
Sensor
Processes**

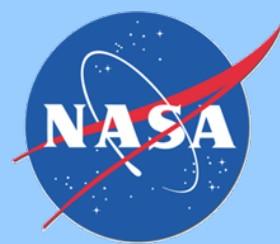
**Intelligent
System Processes**

**Intelligent
Control
Processes**

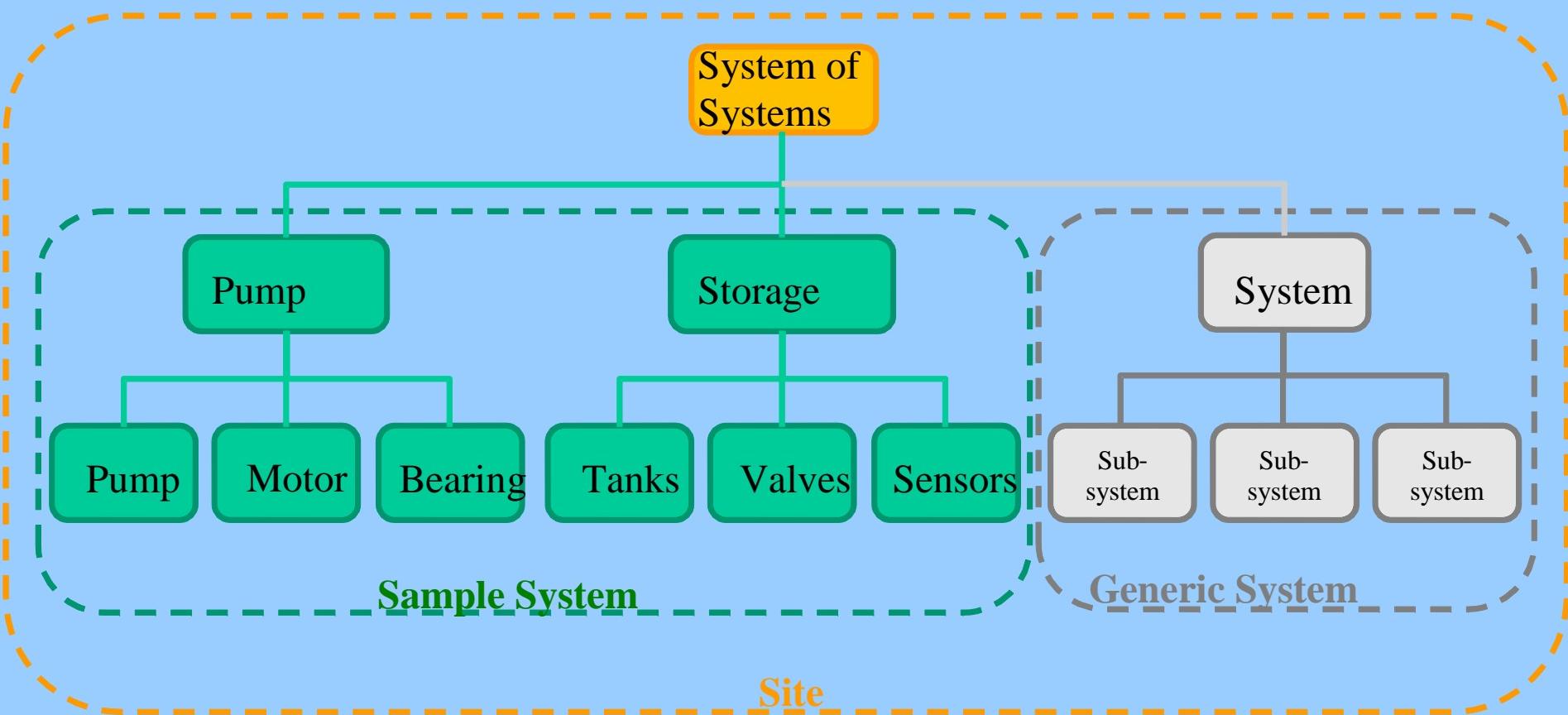
Actuator

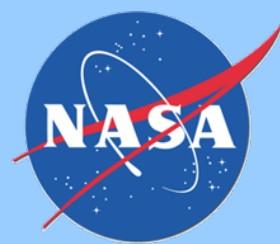
**Intelligent
Components**



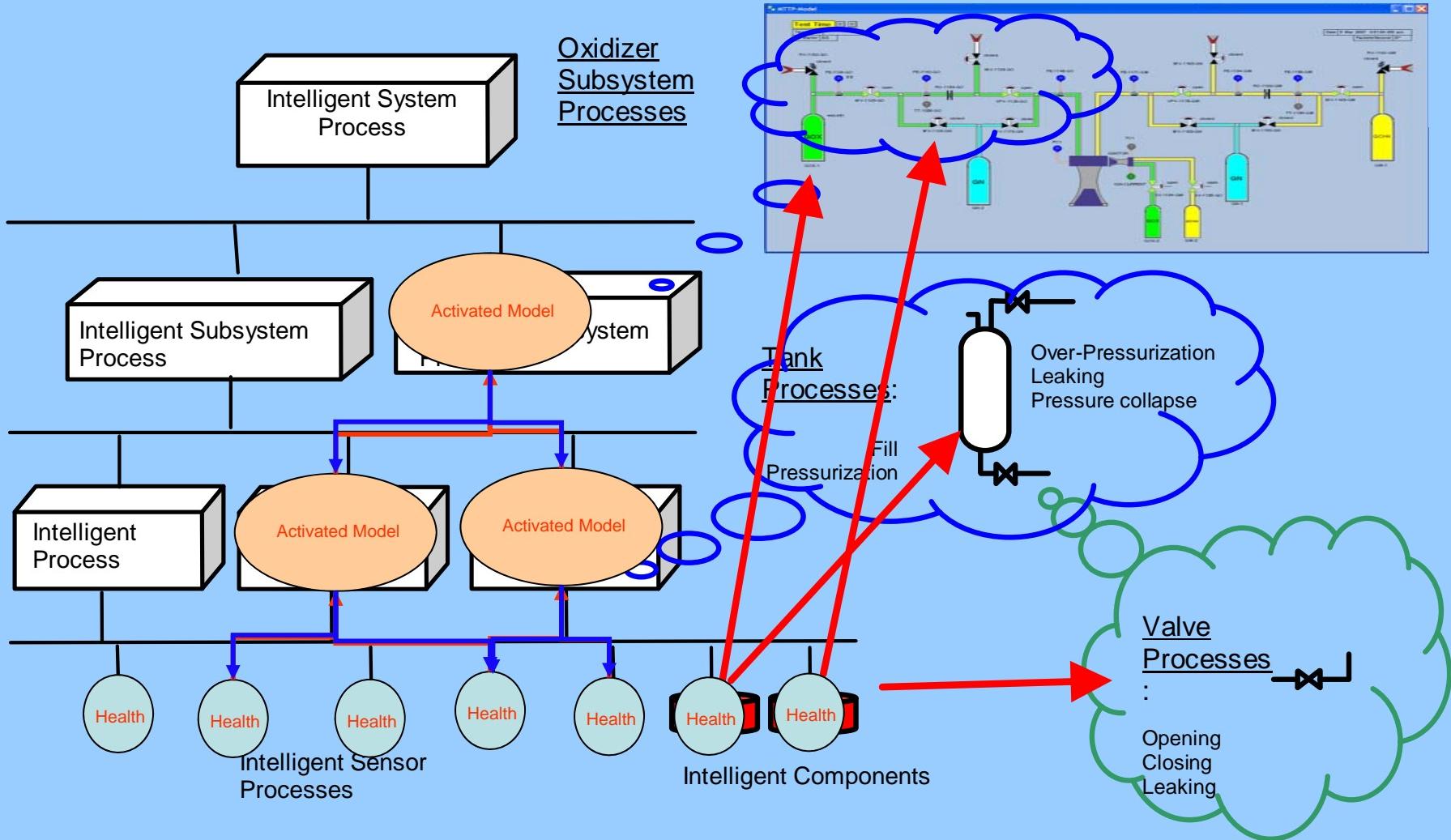


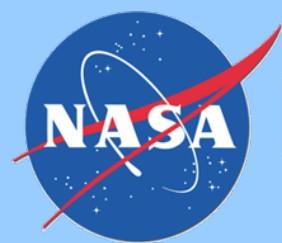
Classic architecture describing how systems are built





Detection and Confirmation of Anomalies Consistency Checking Cycle



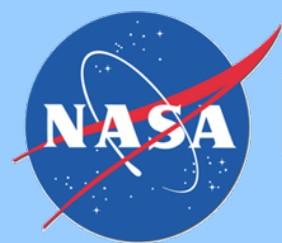


ISHM Capability Development

Standards for ISHM

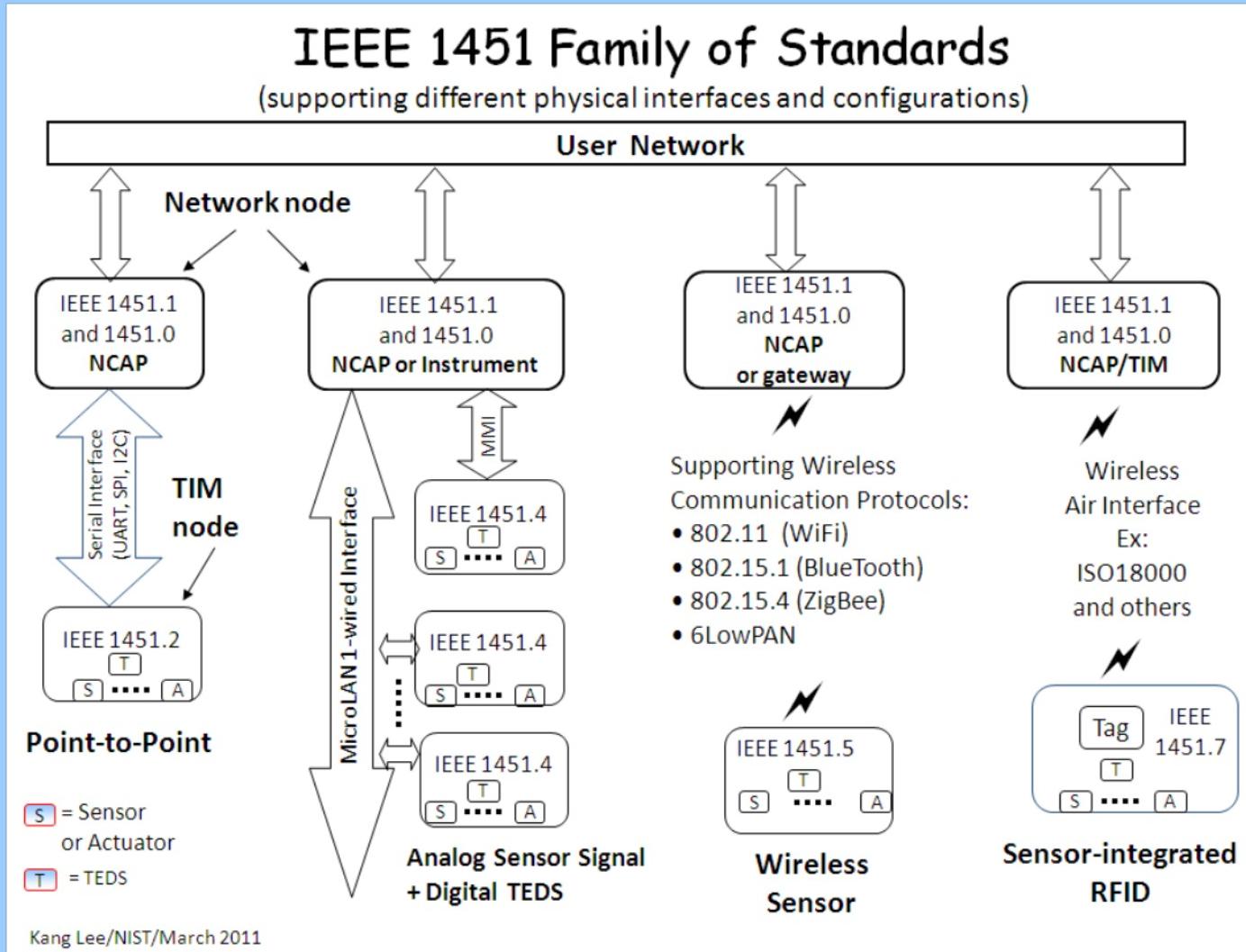
- IEEE 1451 Family of Standards for Smart Sensors and Actuators. Lead by NIST (Dr. Kang Lee).
- OSA-CBM (Open Systems Architecture for Condition Based Maintenance). Developed by industry and government, and transferred to the MIMOSA (Machine Information Management Open Standards Alliance) organization.
- OSA-EIA (Open Systems Architecture for Enterprise Application Integration). MIMOSA organization.

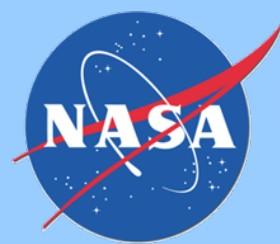
ISHM capability must integrate DIAK across physical, virtual, and discipline boundaries. This is not possible in an affordable manner unless standards are used to achieve plug&play and interoperability.



ISHM Capability Development

Standards for ISHM

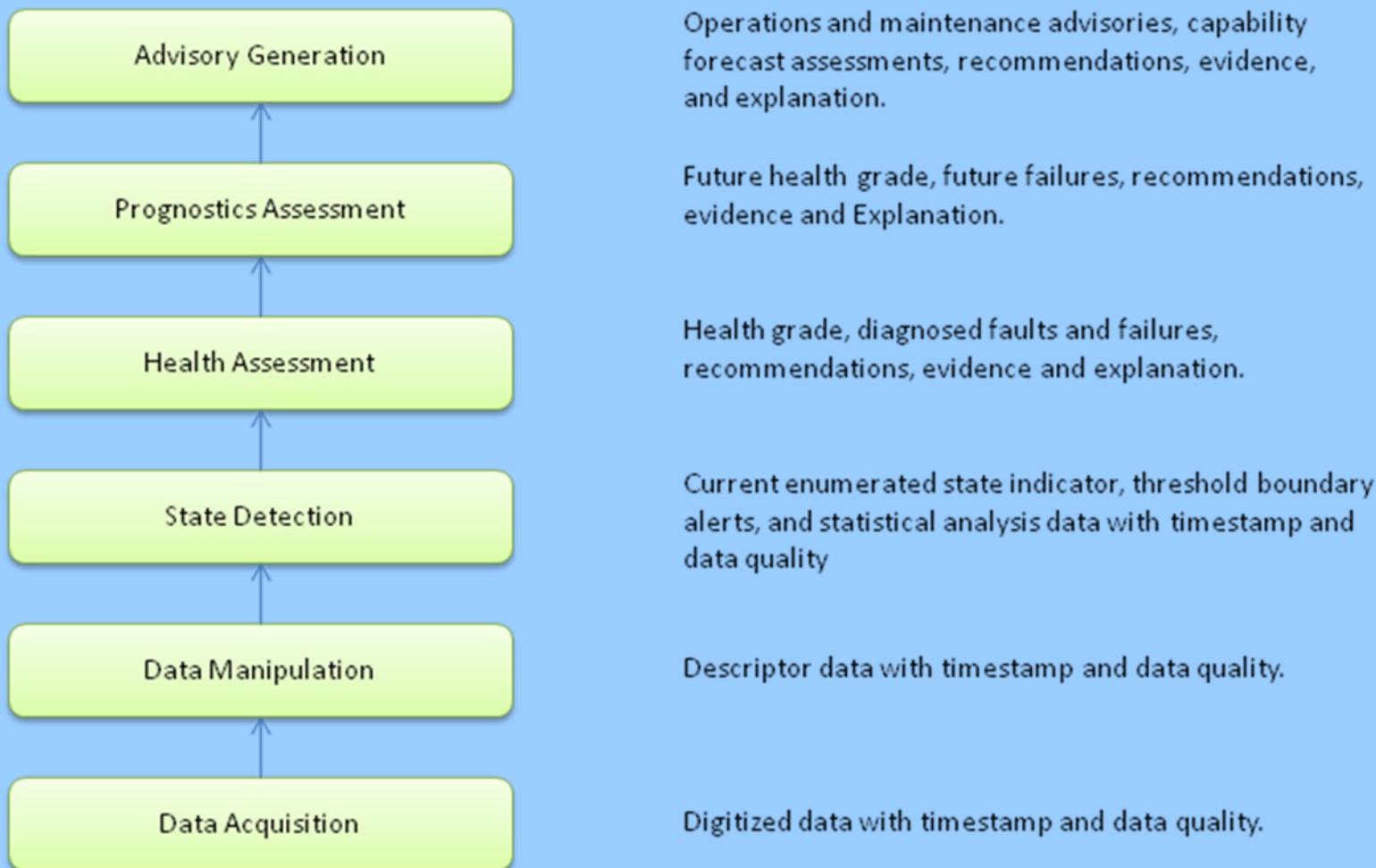


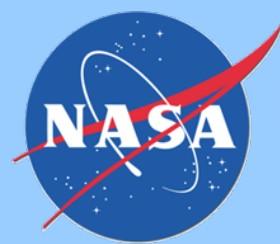


ISHM Capability Development

Standards for ISHM

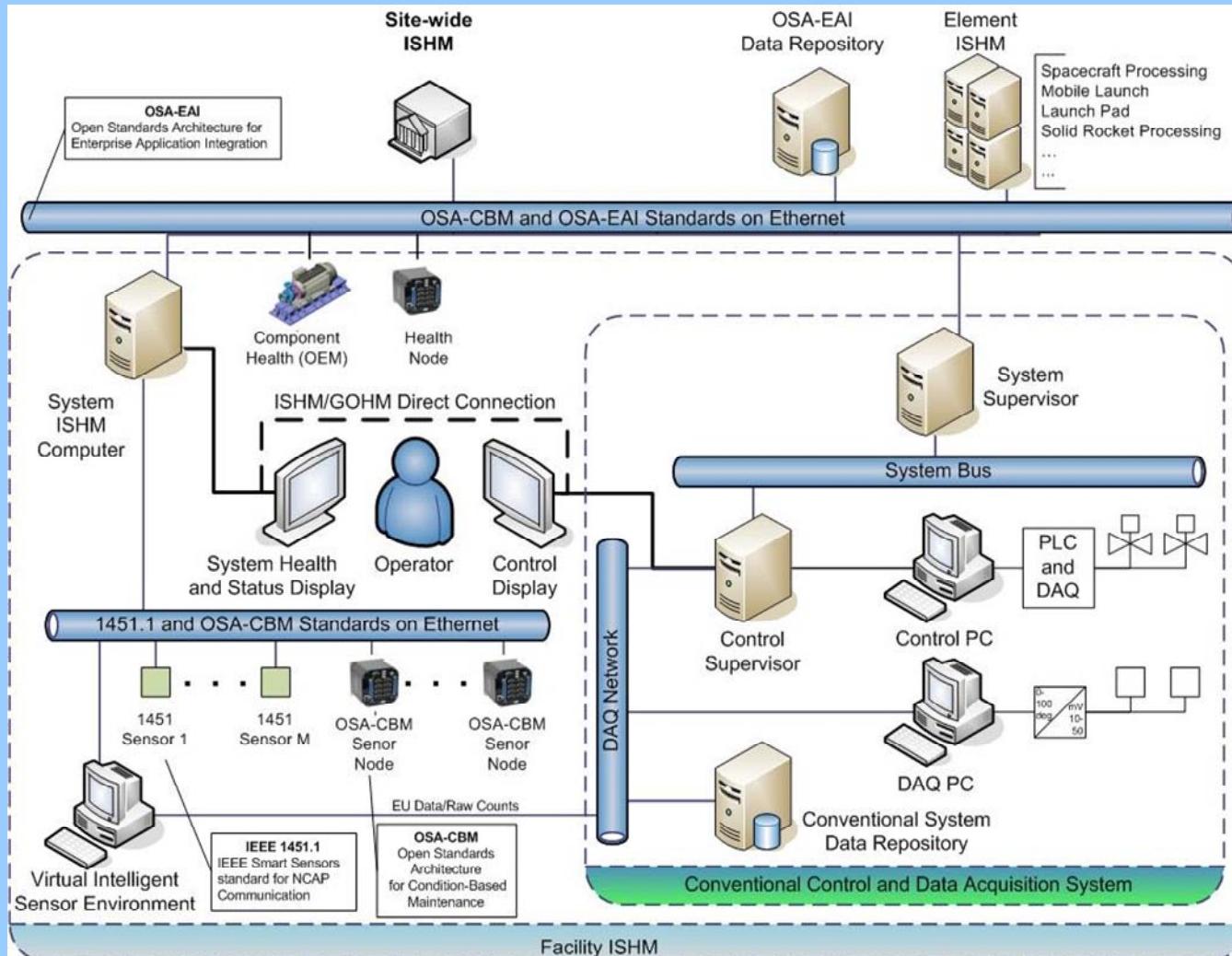
OSA-CBM (MIMOSA)



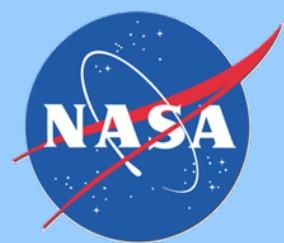


ISHM Capability Development

Standards for ISHM



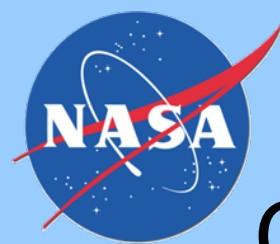
Architecture for pilot ISHM system implemented at NASA Kennedy Space Center, Launch Complex 20 (LC-20) showing the use of IEEE 1451.1, OSA-CBM, and OSA-EAI standards



Software to develop ISHM Domain Models (ISHM-DM's)

A software system for ISHM capability should support all core capabilities by integrating systematically DIAK through the ISHM-DM

- ***Iconic representation of systems objects with visible and virtual links (relationships) used to provide intuitive representation of reasoning and context:*** The mix of object orientation and iconic representation of DIAK provides the ability to intuitively visualize interrelationships and dig deep into details of the ISHM system. As complexity increases, graphical programming and visualization become essential.



Pilot ISHM Implementation Chemical Steam Generator (CSG)

Telewindows Client

File Edit View Layout Go Project Workspace Tools Window Help

Connect to TEDS Database Disconnect from TEDS Database Get All Sensor TEDS Clear All Sensor TEDS

EDS Explorer

By Component...

EDS List

- PE-14A4101-IPA
- TEDS
 - Basic TEDS
 - Bridge Sensor

CSG Domain Map

CSG Detail Layer

CSG Unit #1

Real-Time Plot of PE-14A4101-IPA

Bridge Element Impedance (Ω) 351.3

Bridge Type Full

Calibration Date 2008-07-31

Calibration Period 365

Calibrator's Initials TS

Electronic Datasheet Name Bridge Sensor

Full Scale Electrical Value Precision mV/V

IEEE 1451.4 Template ID 33

Mapping Method Linear

Maximum Electrical Output (V/V) 3.034

Maximum Excitation Level (V) 15

Maximum Physical Value 2000

Measurement Location ID 4101

Minimum Electrical Output (V/V) 0.031

Minimum Excitation Level (V) 10

Minimum Physical Value 0

Real-Time Plot Data:

Time	Value (mV)
18:39:40	1000
18:39:41	950
18:39:42	1000

31 Mon Aug 2009 Current Time HH:MM:SS

Alarms

Root Causes

Repair Actions

Blue Lines

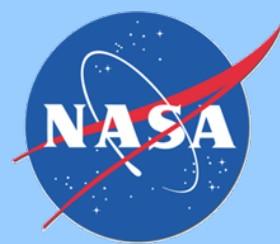
Blue Lines

- PE-14A4047-LO
- BLUE-LINE-DEMO-SENSOR

Red Lines

Red Lines

- TC-14A4132-S



CSG ISHM Domain Model: User Interfaces

Telewindows Client

Blueline Active Monitors

Redline Active Monitors

Blueline Alarm Queues

Redline Alarm Queues

Transducer Electronic Data Sheet Viewing Windows

Blueline Active Monitors

Redline Active Monitors

Blueline Alarm Queues

Redline Alarm Queues

EDS Explorer

By Component..

EDS List

PE-14A4052-LO

TEDS

Basic TEDS

Bridge Sensor

EDS Attributes

Bridge Element Impedance (Ω) 351

Bridge Type Full

Calibration Date 2009-04-21

Calibration Period 365

Calibrator's Initials CA

Electronic Datasheet Name Bridge Sensor

Full Scale Electrical Value Precision mV/V

IEEE 1451.4 Template ID 33

Mapping Method Linear

Maximum Electrical Output (V/V) 3.034

Maximum Excitation Level (V) 15

Maximum Physical Value 1000

Measurement Location ID 4052

Minimum Electrical Output (V/V) 0.015

Minimum Excitation Level (V) 10

Minimum Physical Value 0

Nominal Excitation Level (V) 10

Physical Measurand psi

Read/Write Access Read/Write

Response Time (S) 0.1

Transducer Electrical Signal Type Bridge Sensor

STEAM-PLENUM STEAM-DISCHARGE-PIPE

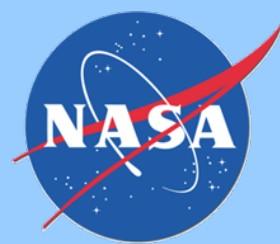
@03232009

Table: BLUELINE-ALARM-QUEUE

Target	Message	Priority	Repetitions	Detail
Pe-14a2435-Hd	ACHIEVED - 2009/06/16 12:31:37.406 p.m.	1	1	HYDRAULIC PRESSURE
Tt-14a16-Lo	ACHIEVED - 2009/06/16 12:31:37.406 p.m.	1	1	LOX RUN TANK TEMPERATURE
Pt-14a23-Gr	ACHIEVED - 2009/06/16 12:31:37.406 p.m.	1	1	UHP GN BOTTLE TANK PRESSURE (LOX PRESS)
Pe-14a4183-Gn	ACHIEVED - 2009/06/16 12:31:37.406 p.m.	1	1	1st STAGE GOX PURGE PRESSURE
Pe-14a4184-Gn	ACHIEVED - 2009/06/16 12:31:37.406 p.m.	1	1	2nd STAGE LOX S/D PURGE PRESSURE
Pe-14a4185-Gn	ACHIEVED - 2009/06/16 12:31:37.406 p.m.	1	1	MAIN STAGE LOX S/D PURGE PRESSURE
Pe-14a4023-Go	ACHIEVED - 2009/06/16 12:31:37.406 p.m.	1	1	GOX SUPPLY PRESSURE

Table: REDLINE-ALARM-QUEUE

Target	Message	Priority	Repetitions	Detail
Pe-14a4117-Ipa	EXCEEDED - 2009/06/16 12:33:56.967 p.m.	1	1	Loss of IPA Main Stage Interface Pressure



CSG ISHM Domain Model: Blueline/Redline User Interfaces

Telewindows Client

File Edit View Layout Go Project Workspace Tools Window Help

Enter Test Parameters IRIG TO Time: 2009:167:12:33:54:883:5 Current Relative Test Time: 2.044 Start Test Sequence Menu User Mode Developer Simulation A RC M L Ready

Bluelines

- PT-14A31-GN
- PE-14A235-HD
- PE-14A2215-CW
- TC-14A4046-LO
- TC-14A4040-LO
- TT-14A16-LO
- PE-14A4185-GN
- PE-14A4183-GN
- PE-14A4184-GN
- PE-14A26-LO
- PE-14A4023-GO
- PE-14A4192-GN
- PE-14A4191-GN
- PE-14A4190-GN
- PE-14A34-JPA
- PT-14A23-GN

Redlines

- PDE-14A4086-S
- PE-14A26-LO
- TT-14A16-LO
- PE-14A4131-S
- PE-14A2435 HD
- PE-14A2215-CW
- TC-14A4128-S
- TC-14A4126-S
- PE-14A4117-JPA
- PE-14A4084-CW
- PE-14A4023-GO

Blueline Details
PE-14A4192-GN
Last Reading Gathered: 591.431
MAIN STAGE IPA S/D PURGE PRESSURE

1200
1000
800
600
400
200
0

Time: 11:29:22 11:29:23 11:29:24 11:29:25

Event Name: ACHIEVED Event Time: 2009/06/16 11:29:24.814978

Blueline Configuration
PE-14A4183-GN
Last Reading Gathered: 586.691
1st STAGE GOX PURGE PRESSURE

1000
800
600
400
200
0

Time: 16 Tue Jun 2009 11:31:14 11:31:15 11:31:16

Redline Details Dialog
PE-14A4117-JPA
Current Reading: 16.584

1000
900
800
700
600
500
400
300
200
100
0

Time: 16 Tue Jun 2009 12:34:30 12:34:45 12:35:00

Event Name: EXCEEDED Event Time: 2009/06/16 12:33:56.967 p.m.

Redline Configuration
PE-14A2215-CW
Last Reading Gathered: 1.436

1000
800
600
400
200
0

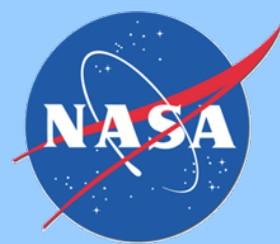
Time: 16 Tue Jun 2009 11:29:57 11:29:58 11:29:59 11:30:00 11:30:01

Blueline Details and Configuration User Interfaces

Redline Details and Configuration User Interfaces

EDS Explorer EDS Attributes

BLUETIME-ALARM-QUEUE REDLINE-ALARM-QUEUE



Example Redline Handling

PLC2 Redline Low Limit Enable Bits

Word 0	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Word 1	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16

PLC2 Redline High Limit Enable Bits

Word 10	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Word 11	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Word 12	47	46	45	44	43	42	41	40	39	38	37	36	35	34	33	32
Word 13	63	62	61	60	59	58	57	56	55	54	53	52	51	50	49	48
Word 14	79	78	77	76	75	74	73	72	71	70	69	68	67	66	65	64
Word 15	95	94	93	92	91	90	89	88	87	86	85	84	83	82	81	80
Word 16	111	110	109	108	107	106	105	104	103	102	101	100	99	98	97	96

PLC2 Voting Booths 0 1 2 3 4 5 6 7 8 9

Buttons: Reset Current PLC, Reset ALL PLCs, Reset Advance

EN ALM Slave Mode

E2C1PLC1 E2C1PLC2

Seq. Acc. Seconds 0.000

Detect Alarm

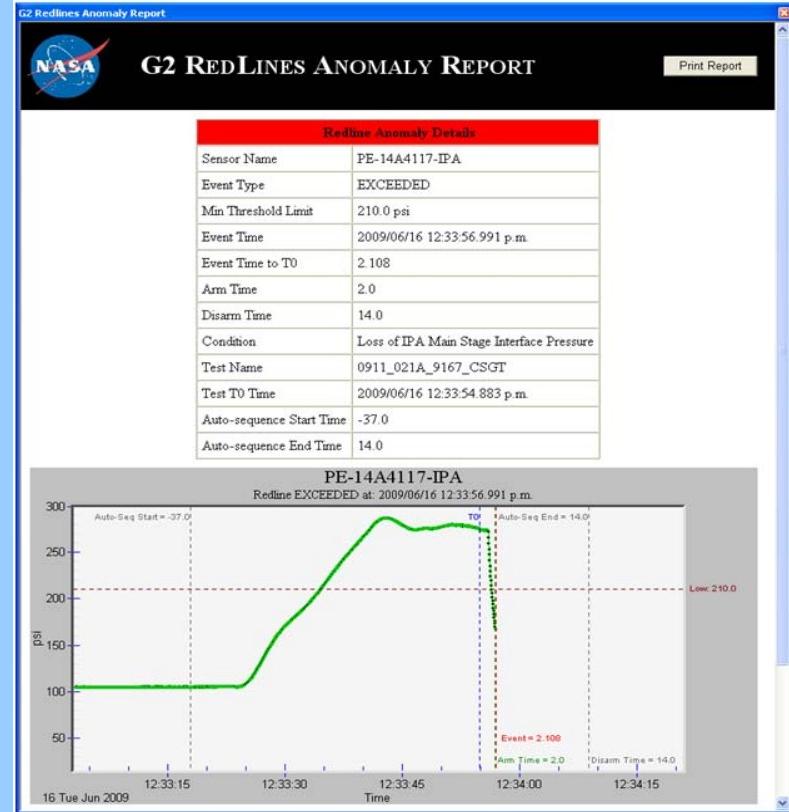
Seq. Clock @ Advance 0.000

Seq. Step @ Advance 0

First Out @ Advance 0

DONE

VS

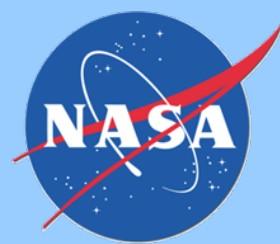


E2 Control Room Redlines UI

- Requires extensive expertise in interpreting events
- Analysis of events takes considerable time and effort
- Only viewed by selected personnel at control room facility

ISHM CSG Model Redlines UI

- Provides easily recognizable details of events
- Immediately accessible to all personnel at control room facility, hardcopy printouts allow for ease of distribution and record keeping
- Additional event and test parameters and associated data are depicted



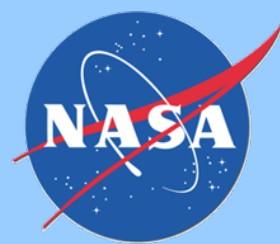
CSG ISHM Domain Model: Redline Event Handling

Auto-generated Redline Report

Navigation to Transducer Where Redline Event Occurred

The screenshot displays the Telewindows Client interface with several windows open:

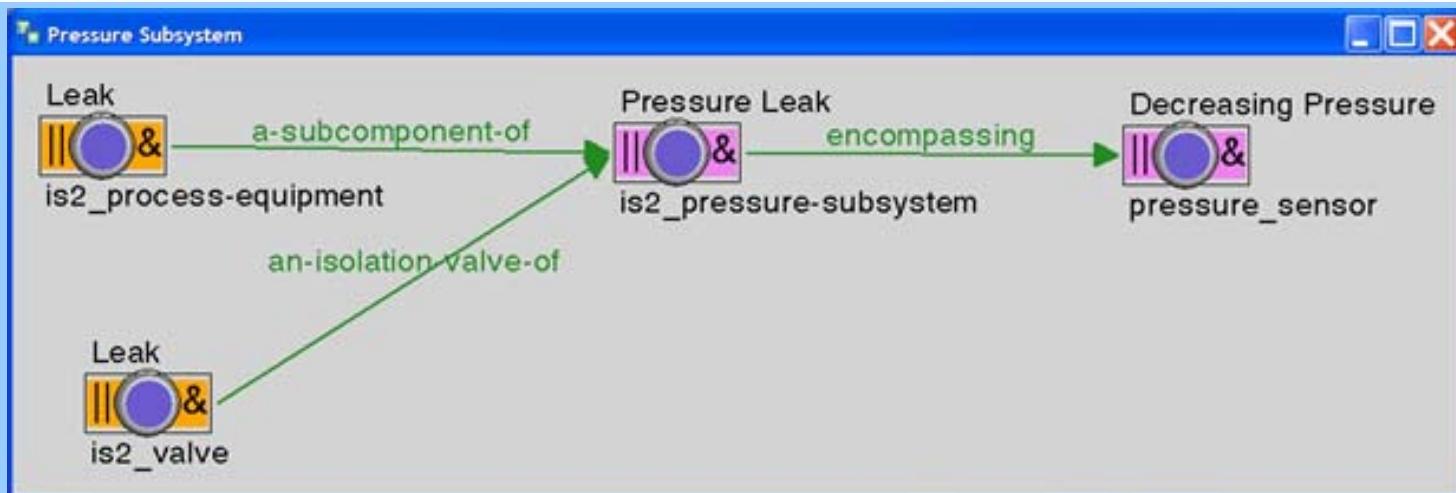
- G2 Redlines Anomaly Report:** Shows a table of Redline Details for Sensor PE-14A4117-IPA, including Event Type (EXCEEDED), Min Threshold Limit (210.0 psi), Event Time (2009/06/16 12:33:56.967 p.m.), and Auto-time (2.0). A red arrow points from this window to the "Auto-generated Redline Report" callout.
- CSG Unit #1:** A schematic diagram of the CSG Unit, divided into Main Stage and 2nd Stage. Various pipes, valves, and transducers are shown. A red arrow points from the "Navigation to Transducer Where Redline Event Occurred" callout to the location of transducer TC-14A4117-IPA in the Main Stage.
- REDLINE-ALARM-QUEUE:** A table listing messages for various targets. One entry is highlighted for Target PE-14A4117-ipa with the message "EXCEEDED - 2009/06/16 12:33:56.967 p.m." and Detail "Loss of IPA Main Stage Interface Pressure". A red arrow points from this table to the "Navigation to Transducer Where Redline Event Occurred" callout.
- BLUELINE-ALARM-QUEUE:** A table listing messages for various targets, showing entries for multiple sensors across different stages.

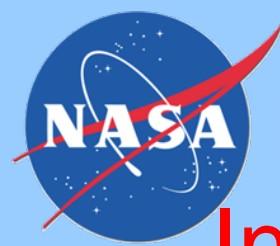


Failures Modes and Effects Analysis (FMEA)

MIL-STD-1629A(2) NOT 3

ID #	Item-Functional Identification	Function	Failure Modes and Causes	Mission Phase-Operational Mode	Failure Effects			Failure Detection Method	
					Local End Effects	Next	Higher Level		
						Higher			
	Process Equipment	Fluid feed subsystem	Leak	Sealed subsystem maintaining pressure		Pressure leak	Decreasing pressure measurement	Identify sealed subsystem, and check pressure sensors for decreasing pressure.	





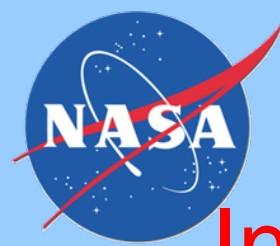
ISHM Capability Development

Intelligent Sensors and Components

Smart Sensor/Actuator (NIST)

“The IEEE (Institute of Electrical and Electronics Engineers) 1451 smart transducer interface standards provide the common interface and enabling technology for the connectivity of transducers to microprocessors, control and field networks, and data acquisition and instrumentation systems. The standardized TEDS specified by IEEE 1451.2 allows the self-description of sensors and the interfaces provide a standardized mechanism to facilitate the plug and play of sensors to networks. The network-independent smart transducer object model defined by IEEE 1451.1 allows sensor manufacturers to support multiple networks and protocols. Thus, transducer-to-network interoperability is on the horizon. The inclusion of P1451.3 and P1451.4 to the family of 1451 standards will meet the needs of the analog transducer users for high-speed applications. In the long run, transducer vendors and users, system integrators and network providers can all benefit from the IEEE 1451 interface standards [1].”.

“Intelligent Sensor” is a “Smart Sensor” with the ability to provide the following functionality: (1) measurement, (2) measure of the quality of the measurement, and (3) measure of the “health” of the sensor. The better the sensor provides functionalities 2 and 3, the more intelligent it is.



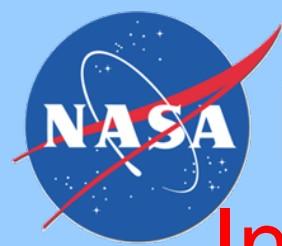
ISHM Capability Development

Intelligent Sensors and Components

Typical Process Models for Sensors

- Noise Level Assessment and History
- Spike Detection and History
- Flat Signal Detection and History
- Response Time Characterization
- Intermittency Characterization and History
- Physical Detachment Characterization and History
- Regime Characterization and History
- Curve Fit on Identified Regimes

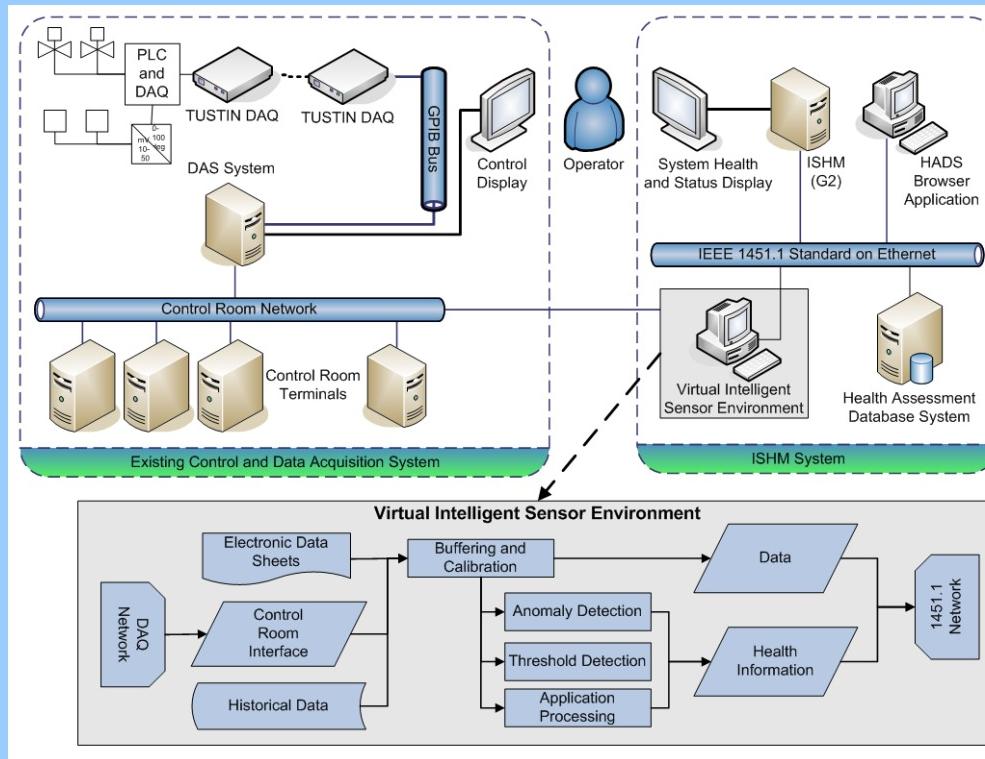
“Intelligent Sensor” is a “Smart Sensor” with the ability to provide the following functionality: (1) measurement, (2) measure of the quality of the measurement, and (3) measure of the “health” of the sensor. The better the sensor provides functionalities 2 and 3, the more intelligent it is.



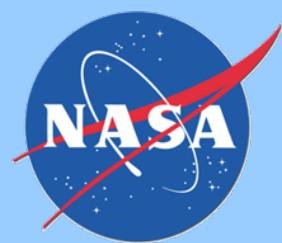
ISHM Capability Development

Intelligent Sensors and Components

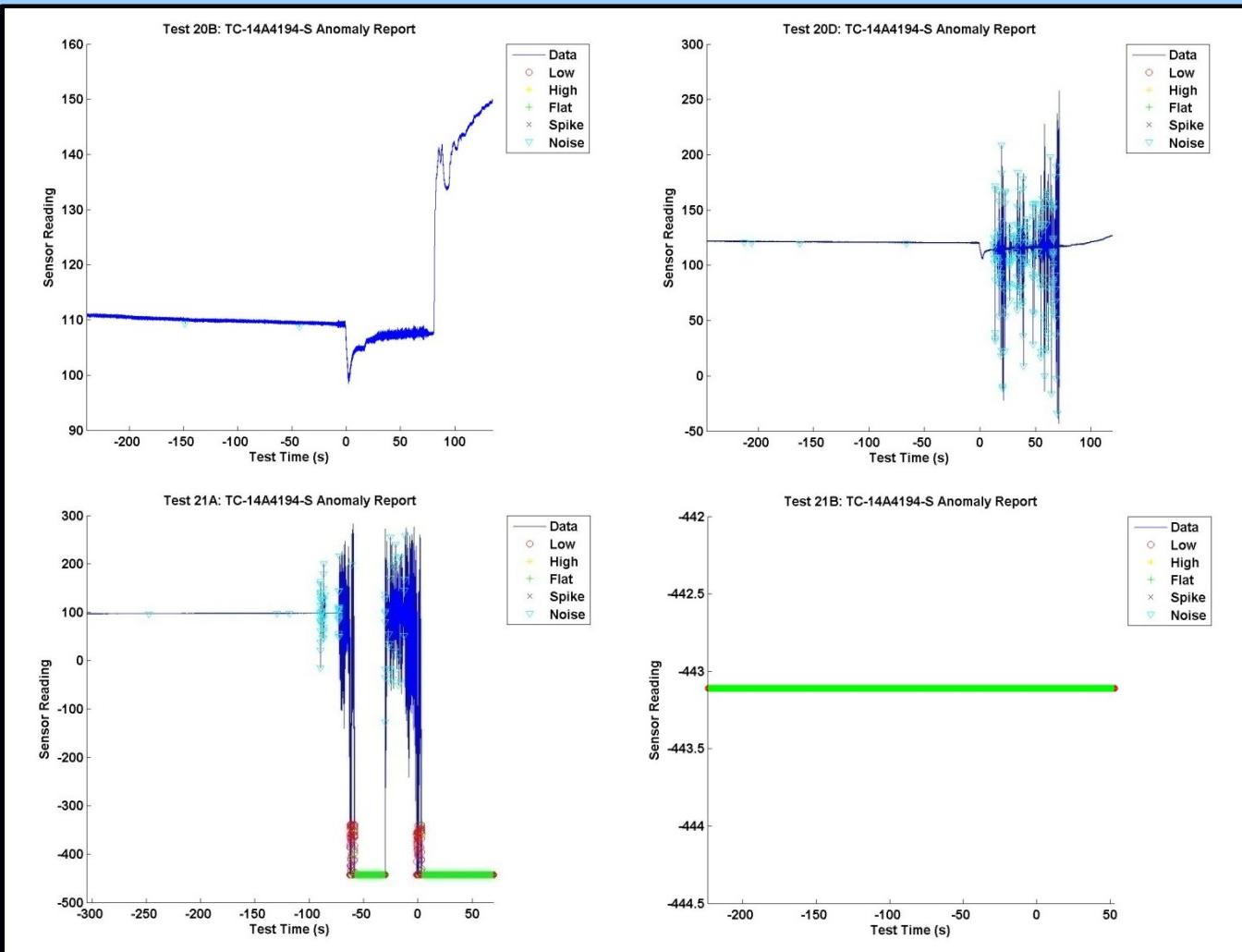
Example Intelligent Sensor Implementations



The Virtual Intelligent Sensor Environment (VISE) converts all classic sensors installed in a rocket engine test stand into “intelligent sensors.”

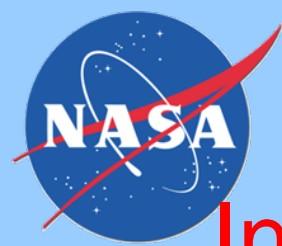


CSG Anomalies Detected



- Evidence of TC degradation detected by VISE anomaly detection
- Advanced notification to determine the health of the whole system before beginning a test

Transducer Anomaly Report Graphs for one sensor in four consecutive tests.



ISHM Capability Development

Intelligent Sensors and Components

Example Intelligent Sensor Implementations



Mobitrum
www.mobitrum.com



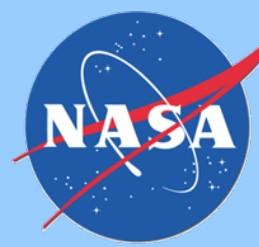
Smart Sensor Systems
www.smartsensorsystems.com



NIST
www.mel.nist.com



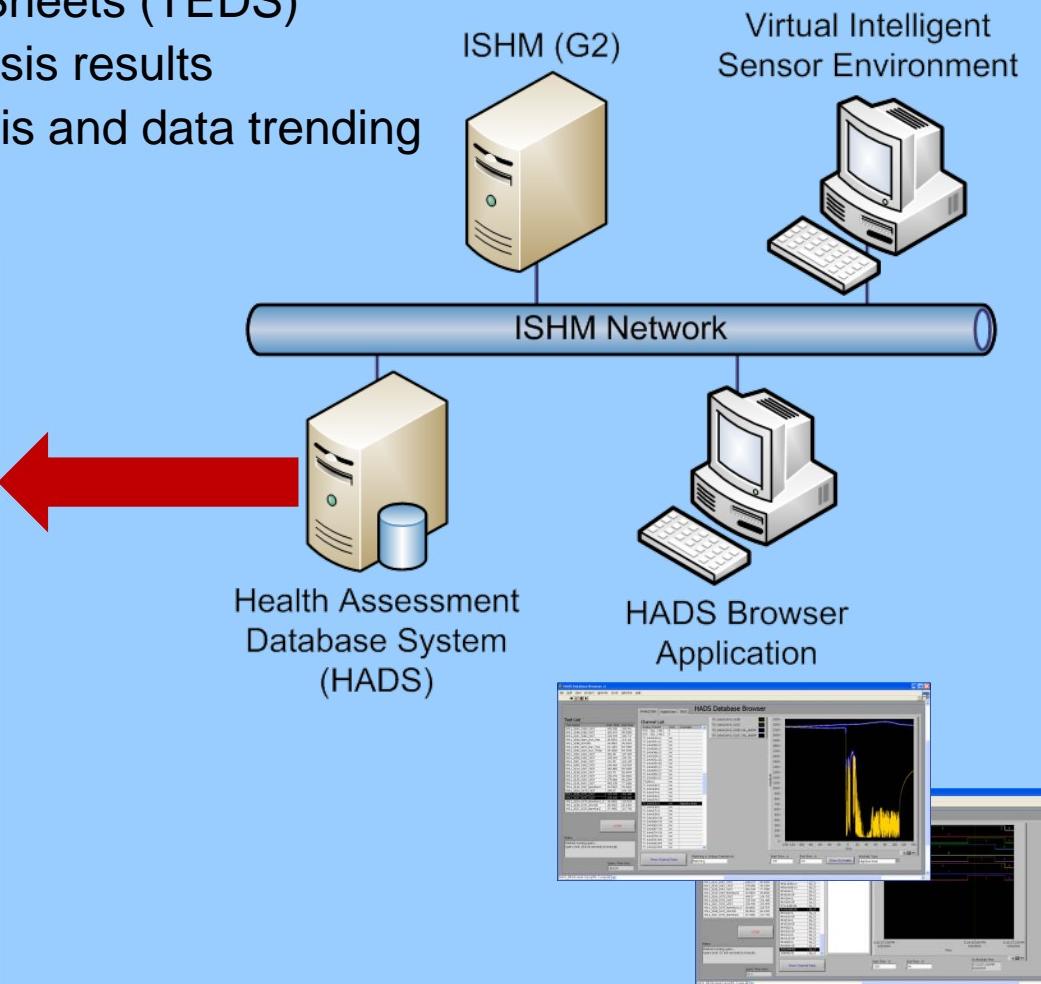
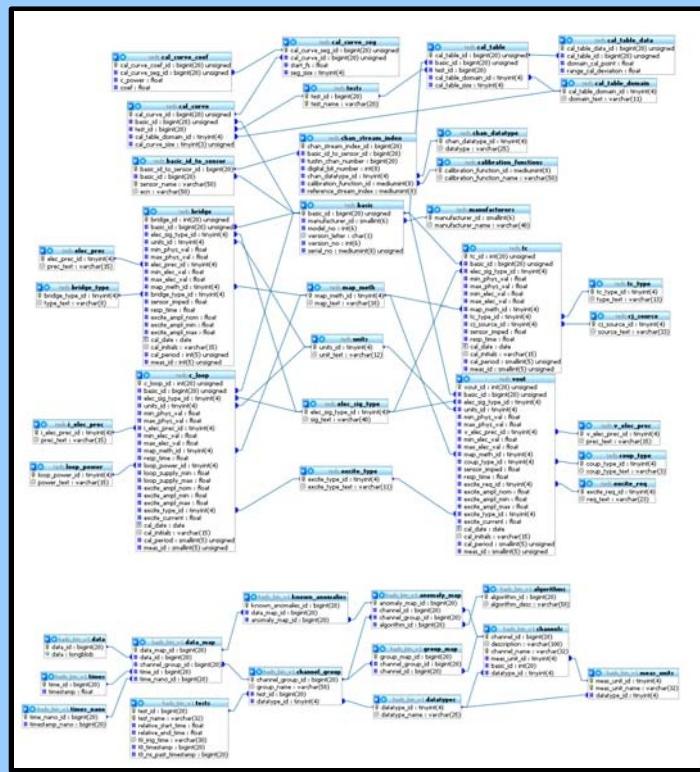
E sensors
www.eesensors.com

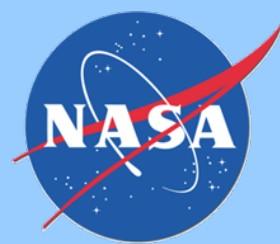


Health Assessment Database System

HADS

- Health Electronic Data Sheets (HEDS)
 - Repository of anomalies and algorithms
 - Transducer Electronic Data Sheets (TEDS)
 - Historical test data and analysis results
 - Provides ease of data analysis and data trending





HADS Browser Application

HADS Browser Capabilities

- Allows longitudinal analyses and comparisons with previous test results
- Viewing usage statistics on monitored elements
 - cycle times on valves
 - mean time to failure
- Viewing anomalous events/data trends
- Viewing TEDS

The screenshot shows the HADS Database Browser application window. The title bar reads "HADS Database Browser.vi". The menu bar includes File, Edit, View, Project, Operate, Tools, Window, Help. The main interface has three tabs: Analog Data, Digital Data, and TEDS. The TEDS tab is active, displaying a table of TEDS data for various sensors. The Analog Data and Digital Data tabs show lists of test runs and their details.

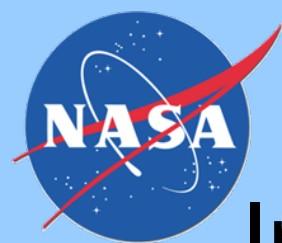
Test Name	Start Time	End Time
0911_019A_9160_C50T	-305.658	100.541
0911_019B_9160_C50T	-262.674	99.520
0911_019C_9160_C50T	-229.078	100.717
4911_019A_Norm_Run_One	-20.0521	114.141
4911_019B_ADV250	-18.9601	45.232
4911_019C_Norm_Run_Two	-21.1961	84.665
4911_019D_Norm_Run_Three	-21.1961	104.764
0911_020A_9162_C50T	-302.99	107.405
0911_020B_9162_C50T	-239.294	134.701
0911_020C_9162_C50T	-311.05	122.145
0911_020D_9162_C50T	-246.462	119.533
0911_021A_9167_C50T	-304.866	69.3285
0911_021B_9167_C50T	-223.75	52.6444
0911_021C_9167_C50T	-226.074	56.9204
0911_021D_9167_C50T	-278.066	46.1284
0911_022A_9170_C50T	-305.959	100.566
4911_021D_9167_NormRun0	-43.9923	40.4002
0911_022A_9170_C50T	-349.07	134.772
0911_022B_9170_C50T	-135.709	151.489
0911_022C_9170_C50T	-135.949	141.949
4911_022A_9170_NormRun1_0	-38.6602	122.533
4911_022B_9170_ADV250	-98.0522	60.1404
4911_022C_9170_NormRun2	-97.4482	117.745

Below the table, there is a "STOP" button and a status message: "Finished running query... Query took 37.100 seconds to execute."

At the bottom left, it says "Query Time (sec) 37.1".

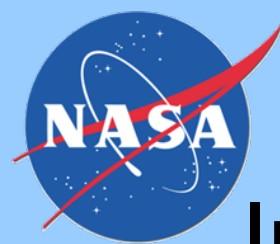
The bottom status bar shows "HADS_BIN Browser.viproj\My Computer" and "IONI-CURR".

Analog Data - Digital Data - TEDS \$ multiple channels

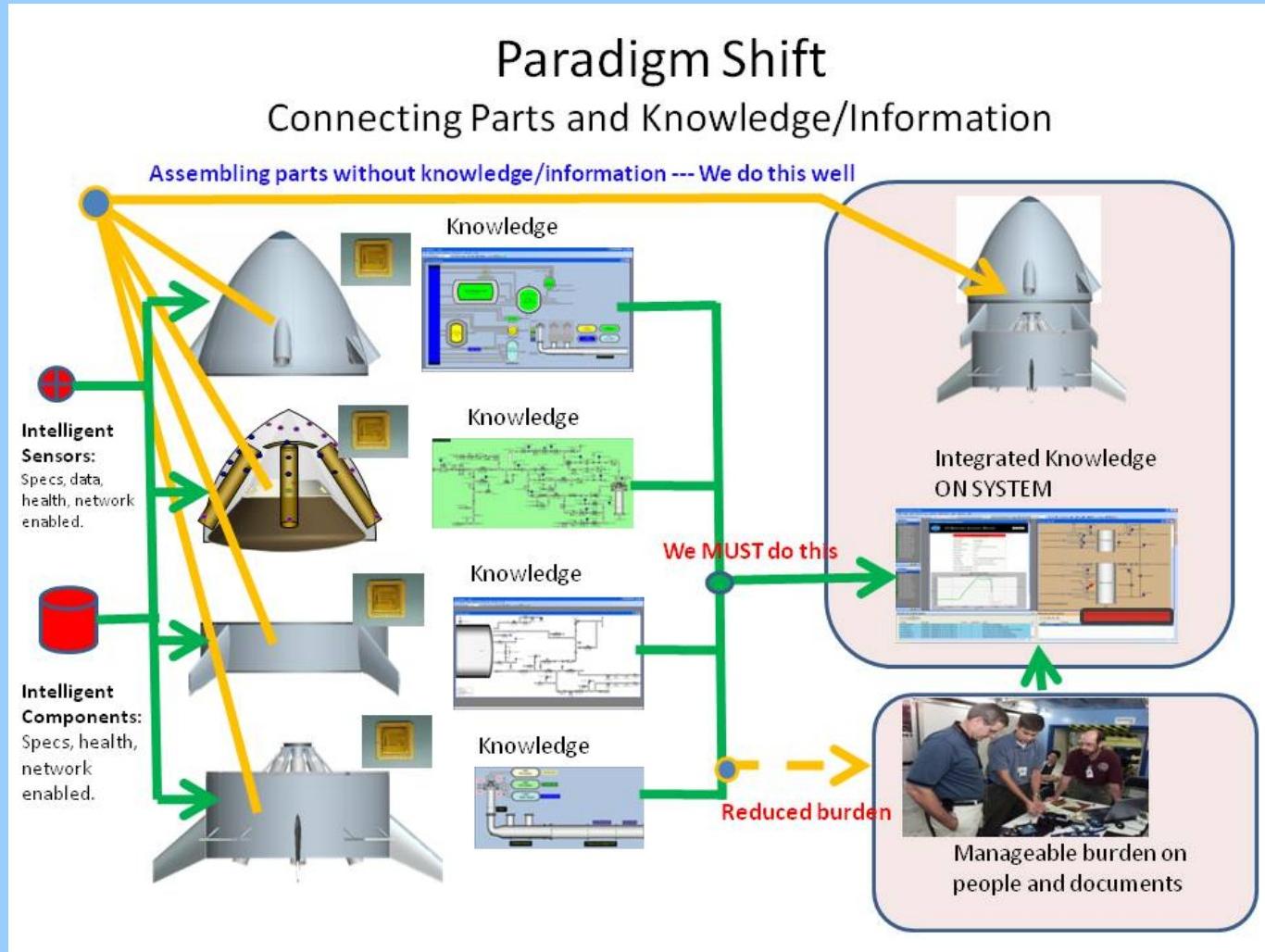


ISHM in Systems Design, Integration, and Engineering (SDI&E)

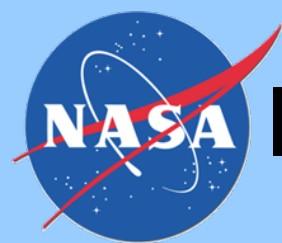
- SDI&E practices are employed to build complex systems.
- SDI&E for aerospace systems has developed into its own discipline, although theories and concepts have not been adequately formalized in an academic sense.
- The role of ISHM in SDI&E is linked to the concept of ISHM-DM's, whereby every element that is part of a system comes with its own ISHM-DM that can be rolled-up into an overall system ISHM-DM in a plug&play approach.
- When two elements are assembled, the ISHM-DM of each element is incorporated into the ISHM-DM of the assembly. In this manner, DfAK compartmentalized in each element becomes immediately available and useful to the ISHM-DM of the assembly.



ISHM in Systems Design, Integration, and Engineering (SDI&E)



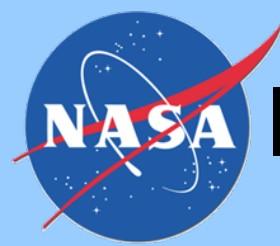
ISHM concept for systems integration of ISHM-DM's



Intelligent Control for ISHM-Enabled Systems

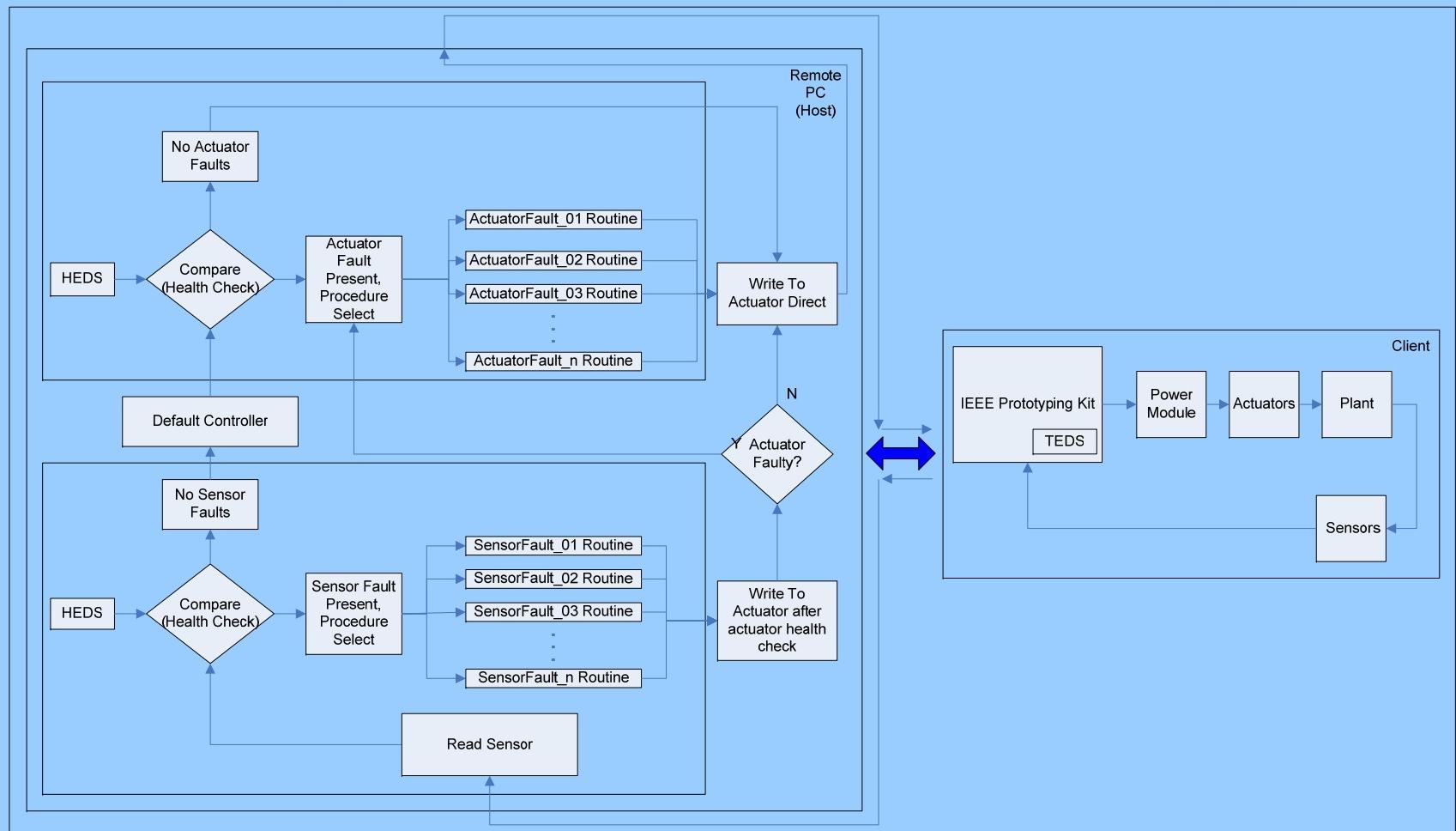
- Control of complex systems that are ISHM-enabled is a nascent area, simply because ISHM itself is also relatively new.
- The objective is for the control function to make use of system health information in order to achieve its objectives.

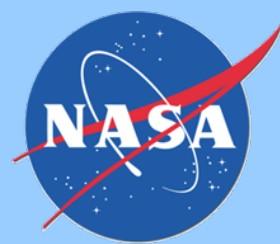
The paradigm implies that control systems become users of health information, while at the same time making use of actuators to help further improve determination of the system health



Intelligent Control for ISHM-Enabled Systems

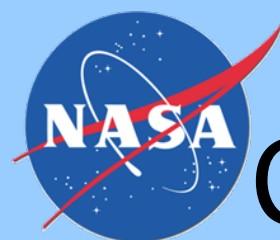
Example Application (Reference 18 of the paper)





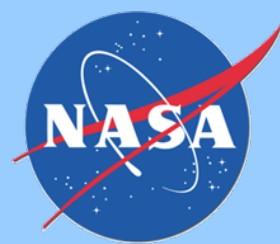
Conclusions

- A sound basis to guide the community in the conception and implementation of ISHM capability in operational systems was provided.
- The concept of “ISHM Model of a System” and a related Data, Information, and Knowledge (DIAK) architecture were described. The ISHM architecture is independent of the typical system architecture, which is based on grouping physical elements that are assembled to make up a subsystem, and subsystems combine to form systems, etc.
- It was emphasized that ISHM capability needs to be implemented first at a low functional capability level (FCL), or limited ability to detect anomalies, diagnose, determine consequences, etc. As algorithms and tools to augment or improve the FCL are identified, they should be incorporated into the system. This means that the architecture, DIAK management, and software, must be modular and standards-based, in order to enable systematic augmentation of FCL (no ad-hoc modifications).
- A set of technologies (and tools) needed to implement ISHM were described. One essential tool is a software environment to create the ISHM Model. The software environment encapsulates DIAK, and an infrastructure to focus DIAK on determining health (detect anomalies, determine causes, determine effects, and provide integrated awareness of the system to the operator). The environment includes gateways to communicate in accordance to standards, specially the IEEE 1451.1 Standard for Smart Sensors and Actuators



Challenges and Opportunities

- EDUCATION
 - Inclusion of ISHM in the design process (Design for ISHM).
 - ISHM concept as a knowledge-based capability.
 - Software environments to build ISHM models.
 - Physics of failure.
 - Anomaly detection (algorithms, approaches, strategies).
 - Failure modes and effects analysis (FMEA) and root-cause tree analysis concepts and automation.
 - Software environments supporting processing within networked intelligent elements and standards-based interaction.
 - User interfaces: “integrated awareness of system elements.”
- RESEARCH
 - ISHM incorporates multiple disciplines: physics modeling or modeling of any phenomena occurring in a system, algorithm development, knowledge systems, user interfaces, software environments, intelligent systems, standards, network capabilities, etc.
 - Laboratory/pilot implementations (e.g. university power plant) for validation of the research. Very few “low functional capability” ISHM systems have been implemented (Space Shuttle Main Engine, Boeing 777 are the more visible cases). Experimental validation will bring high visibility to potential users/investors (NASA, DoD, DoE, Chemical and Oil industries, power plants, ships, etc.).
 - ISHM is in its infancy, but can develop very fast. Three notable annual conferences specific to ISHM are on-going:
 - ISHM Conference (usually in Covington Ky. Or Cincinnati, OH), started by AFRL (In its fifth year or so).
 - Prognostics and Health Management Annual Conference (its second event to take place at the end of September, in San Diego).
 - AIAA Infotech@jAerospace Conference has added ISHM as a technical area.
 - ISHM capability can be implemented and validated without disturbing on-going normal operations.



MOON

WEEEEEE!!!

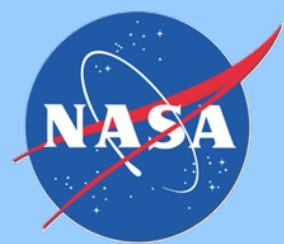
EARTH

It looks like
someone needs
a hug!

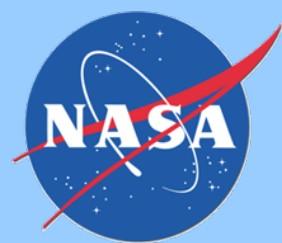
HEY! A little help
over here!

Where did I
leave the
keys?

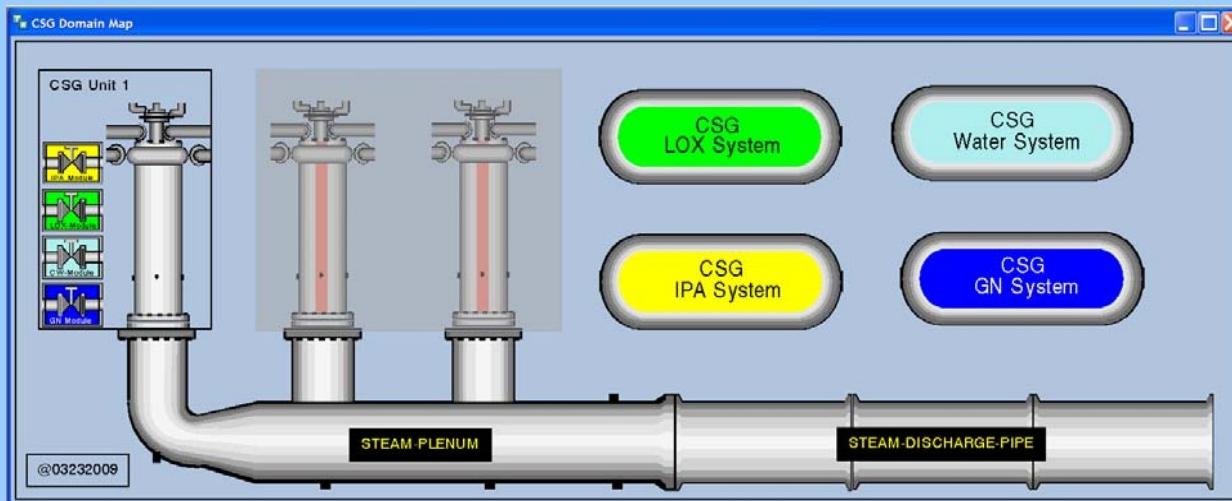
Mars Colony



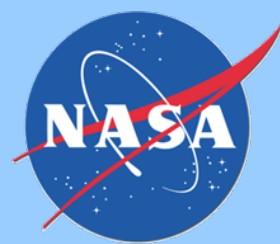
Backup Slides



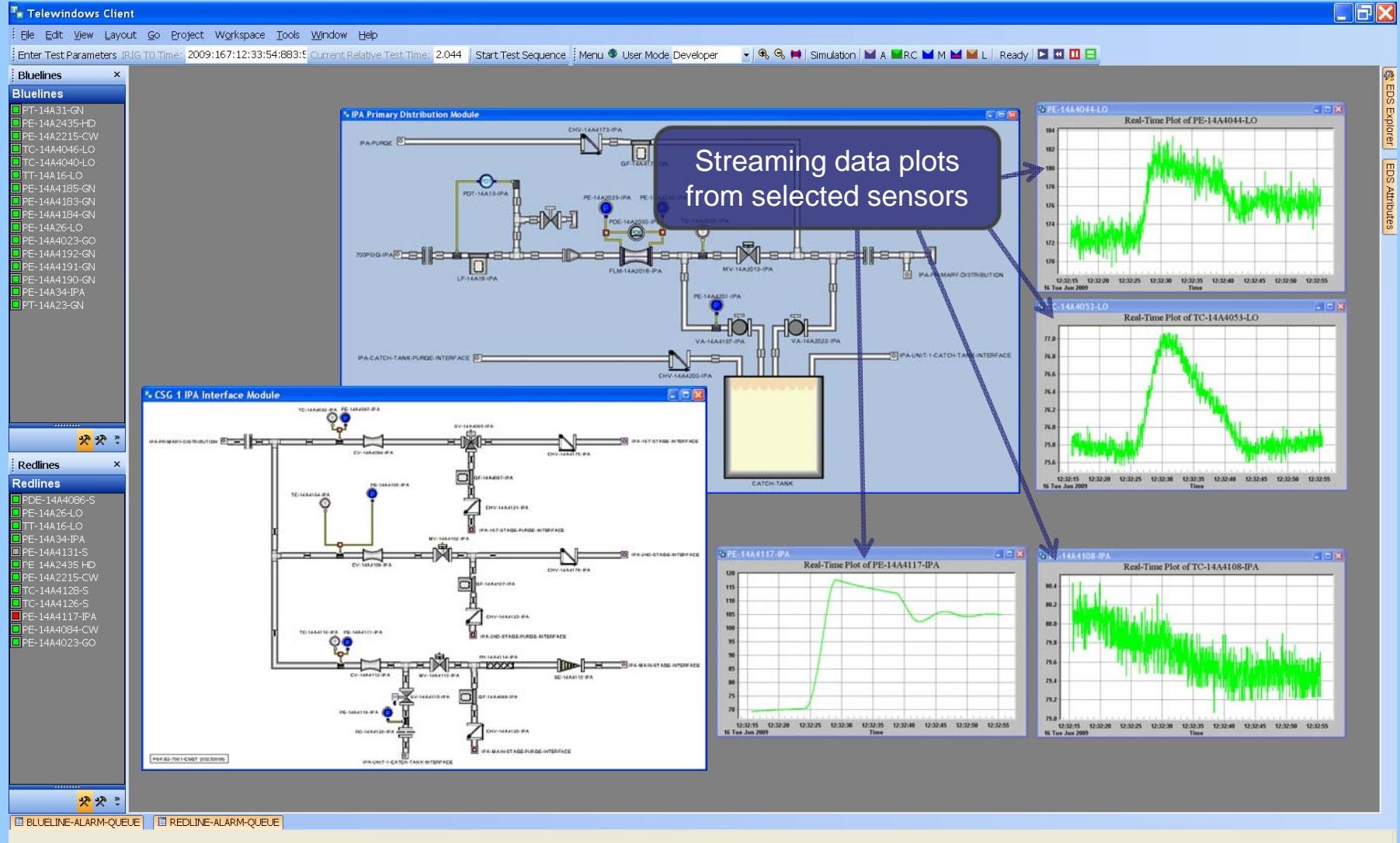
CSG ISHM Domain Model: Top Layer View

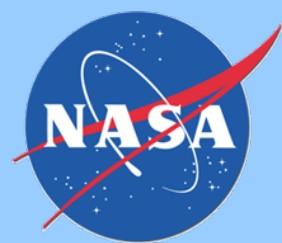


ISHM Domain
Model
Top Layer

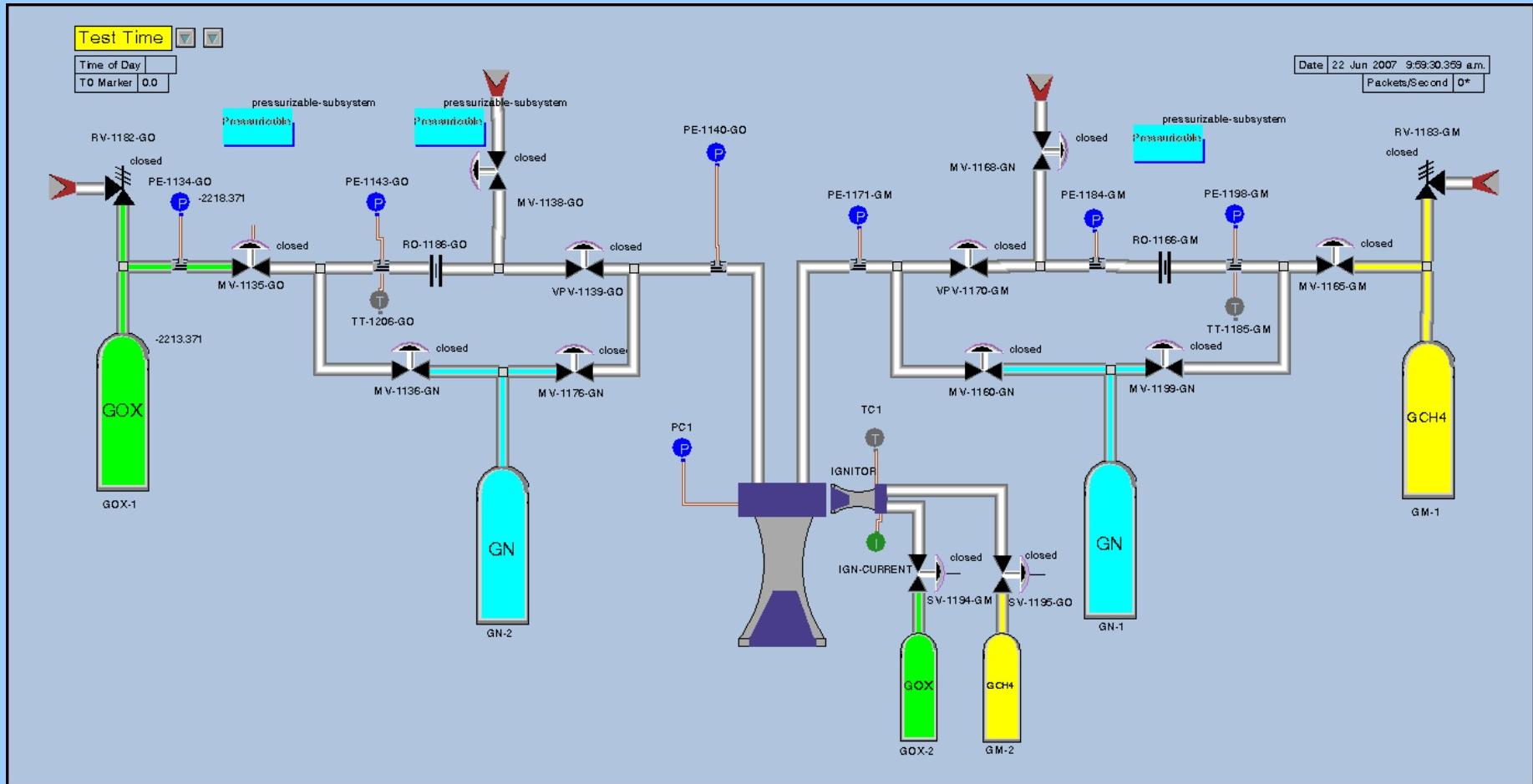


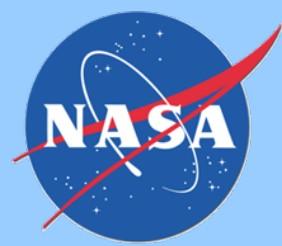
CSG ISHM Domain Model: Transducer Data Plots





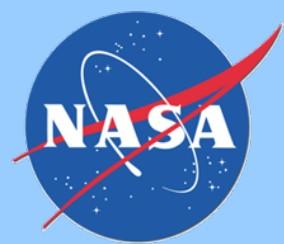
Elements of an ISHM System: ISHM Model - Proximate Cause Analysis



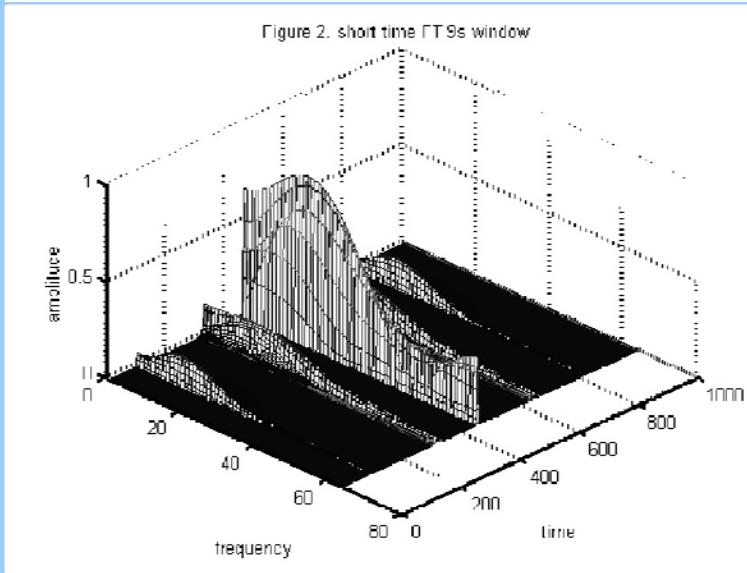
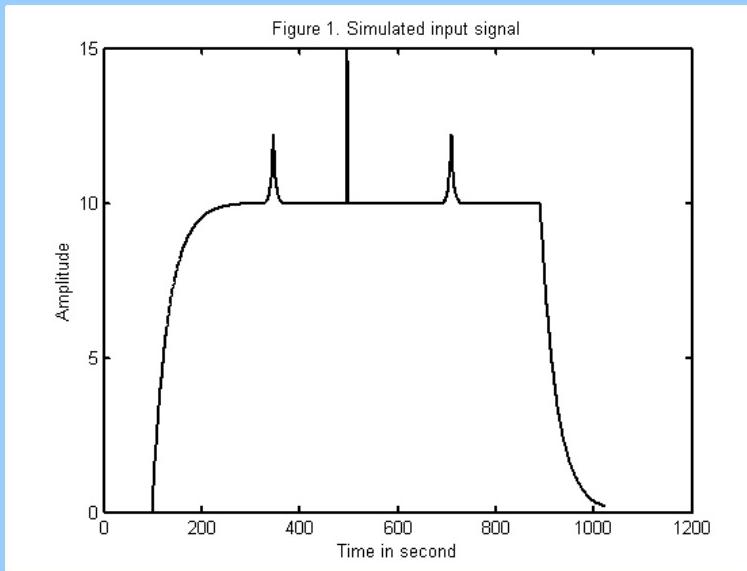


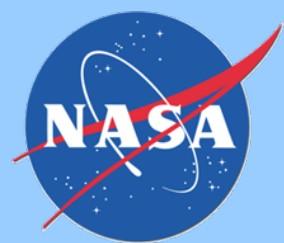
List of Anomaly Detection Capabilities

Anomaly/Behavior	Demonstrated Cause	Detection Approach
Leaks (pipes, valves, etc.)	Various	Checking for pressure leaks using the concept of Pressure Subsystems.
Valve state undetermined	Defective feedback sensor Controller failure	Determines valve state by checking consistency of command, feedback, open/close switches, and pressure conditions upstream and downstream.
Valve oscillation	Fluid contamination in hydraulic supply	Compare running standard deviation of command versus feedback.
Valve stuck	Fluid contamination in hydraulic supply Seat seizure	Feedback remains horizontal while command changes.
Excessive noise, spikes, etc.	Interference	Running standard deviation exceeds set limits. Thresholds violations during short time spans (compared to sensor time-constant).
Degradation	Wear, aging	Trend detection using curve fitting and determination of time-constants.
Prediction-Measurement mismatch	Various	Use predictive model (e.g. from Modeling & Analysis Group) to predict sensor values and compare with measurements.



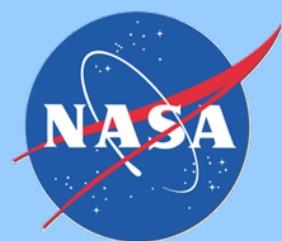
Short-Time Fourier Transform Segmentation



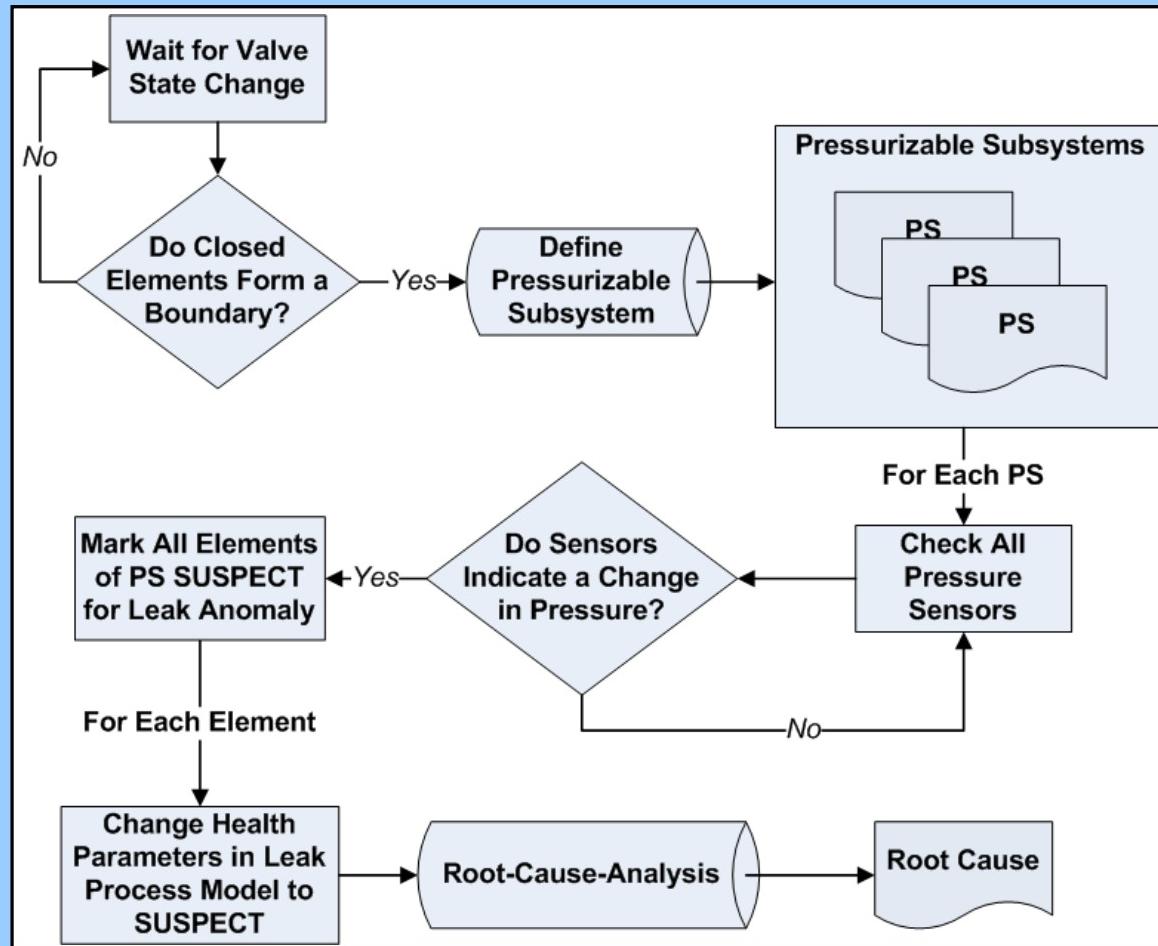


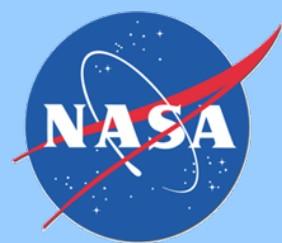
Determining Valve-State

Valve State	Command	Feedback	Open limit	Closed Limit	Associated Sensors
Open	Open	Open	True	False	Agree with model
	Healthy				
Closed	Closed	Closed	False	True	Agree with Model
	Healthy				

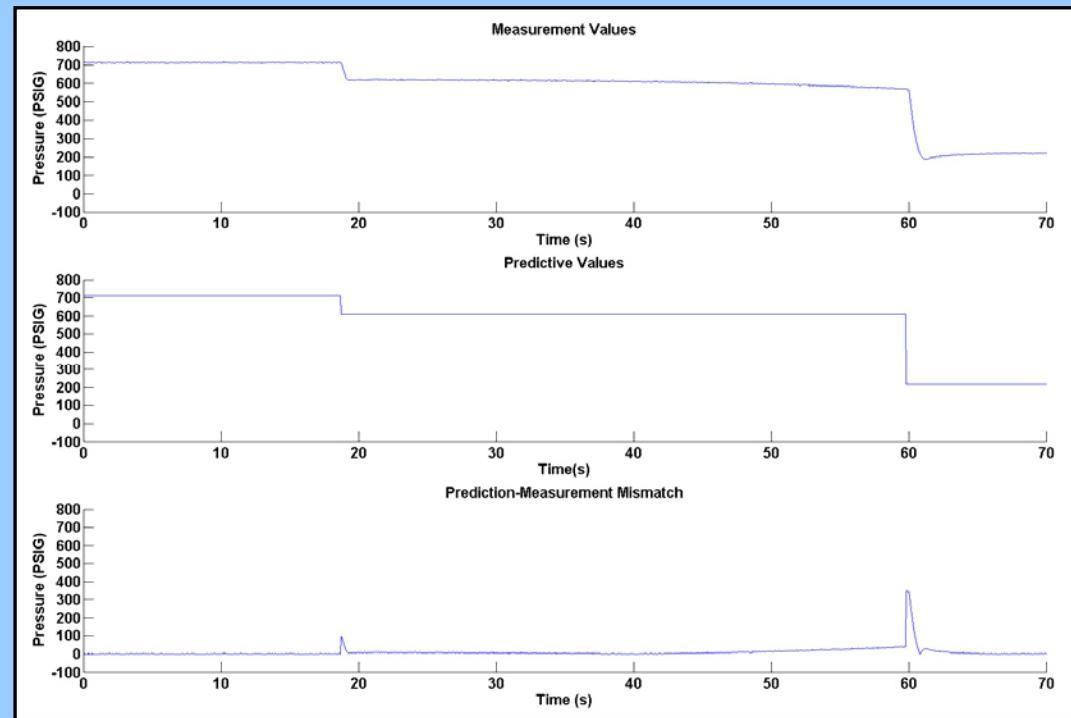
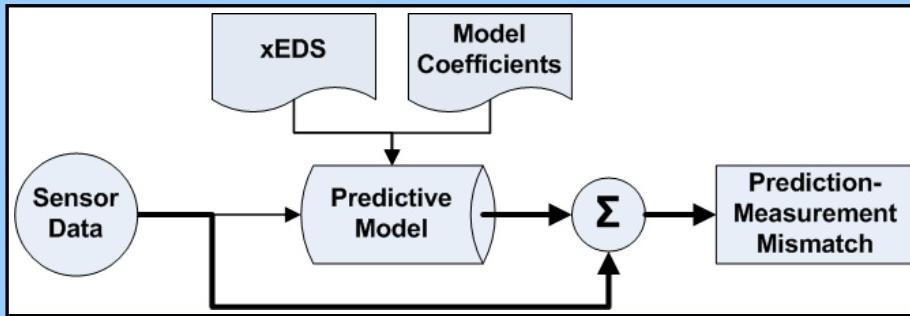


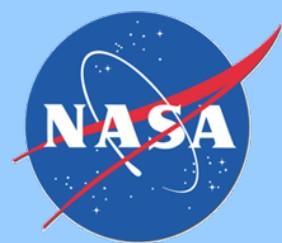
Checking for Pressure Leaks





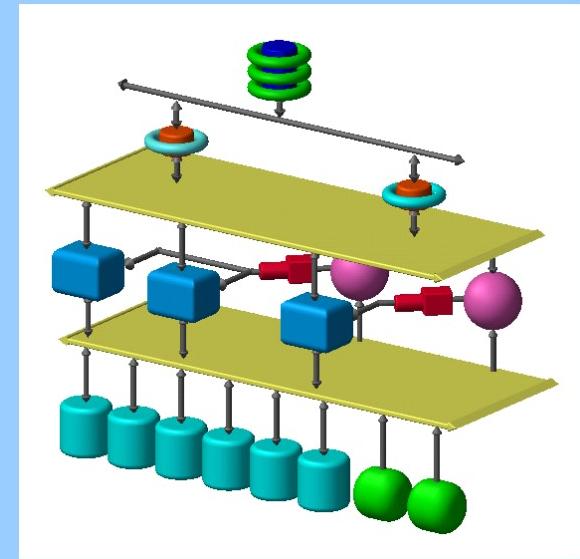
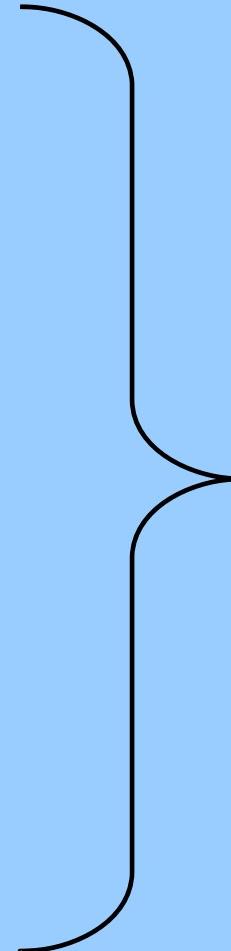
Runtime Predictive Modeling



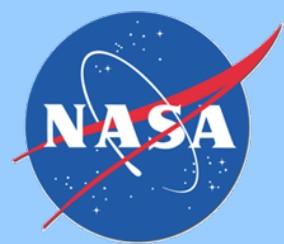


Intelligent Sensors

- Smart sensor
 - NCAP (Go Active, Announce)
 - Publish data
 - Set/Get TEDS
- Intelligent sensor
 - Set/Get HEDS
 - Publish health
- Detect classes of anomalies using:
 - Using statistical measures
 - Mean
 - Standard deviation
 - RMS
 - Polynomial fits
 - Derivatives (1st, 2nd)
 - Filtering—e.g., Butterworth HP
 - FFT—e.g., 64-point
 - Wavelet Transforms (segmentation)
 - Algorithms for
 - Flat
 - Impulsive (“spike”) noise
 - White noise
 - Other (ANN, etc.)



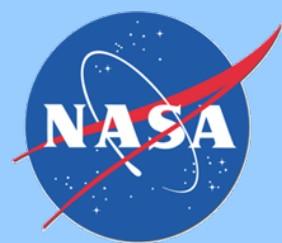
Intelligent Sensors have embedded ISHM functionality and support **Smart Sensor** standards



Software to develop ISHM Domain Models (ISHM-DM's)

A software system for ISHM capability should support all core capabilities by integrating systematically DlaK through the ISHM-DM

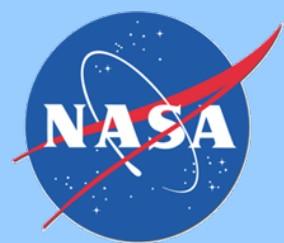
- ***Object orientation:*** object representation of system physical elements and associated process models is the best way to embed DlaK in a systematic and in an organized manner.
- ***Distribution of ISHM-DM's within and across networks:*** ISHM-DM's might be distributed among processors connected to a network, simply because it is necessary to use parallel processing, and/or ISHM-DM's might be created by different people in various geographic locations



Software to develop ISHM Domain Models (ISHM-DM's)

A software system for ISHM capability should support all core capabilities by integrating systematically DlaK through the ISHM-DM

- ***Distribution across processing units:*** Since multiple process models are expected to be running at any given time, the software environments should support parallel processing.
- ***Inference engine:*** Many tasks require an inference engine. Reasoning and decision making leading to anomaly detection, diagnostics, effects, and prognostics; require contextual integrity and cause-effect analysis using heterogeneous data and information.



Software to develop ISHM Domain Models (ISHM-DM's)

A software system for ISHM capability should support all core capabilities by integrating systematically DlaK through the ISHM-DM

- ***Integrated management of distributed DlaK:*** DlaK must be managed in a way to allow embodiment of systems thinking across elements and subsystems. Often this is enabled by definitions of relationships among elements of systems that can be physically visible (i.e. attached to, belong to a system); or more abstracted relationships, as it relates to involvement by groups of objects in process models.
- ***Definition of dynamic relationships among objects for use in reasoning:*** Often, the framework for reasoning and application of process models changes dynamically with configuration changes, stages of operation, etc.